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Detecting and modelling spatial patterns of urban sprawl in highly fragmented areas: A case study in the Flanders–Brussels region

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ABSTRACT

The Flanders–Brussels region (Belgium) is one of the most urbanised regions in Europe. Since the 1960s the region is subject to urban sprawl, which resulted in highly fragmented landscapes. In this study, urban expansion in the period 1976–2000 is detected using LANDSAT satellite imagery in two contrasting study areas (highly urbanised vs. semi-urbanised) in the Flanders–Brussels area. The highly urbanised study area is characterised by a concentric growth pattern, while the urban expansion in the semi-urban area is much more fragmented. Next, the observed urban sprawl pattern of 2000 was reproduced by means of a spatial model, based on suitability maps. Employment potential, distance to roads and to motorway entry points and flood risk were used to assess the suitability for new built-up land. The observed expansion of the built-up area between 1976 and 1988 was used to calibrate the model parameters. The land cover map of 2000 was used to validate the model output. The analysis shows that the model output should not be interpreted at the level of individual grid cells. At aggregation levels of 240 m × 240 m and above the model produces significant results. The model performance is better in areas with concentric urban sprawl patterns than in highly fragmented areas. Because of its simplicity, the proposed methodology is a useful tool for land managers and policy makers that want to evaluate the impact of their decisions and develop future scenarios.

1. Introduction

Urban sprawl is one of the main challenges in spatial planning in the 21st century. Urban sprawl is defined as a specific form of urban development with low-density, dispersed, auto-dependent and environmentally and socially impacting characteristics (Hasse and Lathrop, 2003). A whole range of consequences and negative implications related with this type of urban development are brought forward in literature. These include increased traffic and demand for mobility (Ewing et al., 2002; Cameron et al., 2004; Kahn, 2000), land use fragmentation and loss of biodiversity (Alberti, 2005), reduced landscape attractivity (Sullivan and Lovell, 2006) and alterations of the hydrological cycle and flooding regimes (Bronstert et al., 2002; Carlson, 2004; McCuen, 2003).

The urban sprawl phenomenon has been studied intensively by North American researchers (e.g. Downs, 1999; Ewing et al., 2002; Hasse and Lathrop, 2003; Lopez and Hynes, 2003). In the past, urban sprawl was regarded as a US phenomenon associated with the low-density outward expansion of the urban areas. Seeds for that growth were already sown during the interwar period. They include a rapid increase of private car ownership and rising incomes (Nechyba and Walsh, 2004). Later on, similar urban sprawl processes were described in Europe. Table 1 shows the average percentage of built-up land in both the European Union (European Environment Agency [EEA], 2007) and the United States (National Resources Conservation Services, 2007). The results show that the overall proportions of built-up area reported for the US and the EU are similar. Nevertheless, urban sprawl patterns in Europe are quite different from those in North America because of the historical and societal context (EEA, 2006). Most European cities kept their historical compact structure till the beginning of the 1960s. A typical European city was characterised by a dense historical core and a relatively small urban fringe surrounded by rural areas. Due to the economic growth in the 1960s and 1970s most European cities expanded outside of their historical cores. Today urban sprawl is a common phenomenon throughout Europe and is expected to continue during the next decades (Dieleman and Wegener, 2004; EEA, 2006; Kasanko et al., 2006).

Within the European context, the situation of Flanders – the northern part of Belgium – and the Brussels-Capital Region (Fig. 1) is quite remarkable. The densely populated area (515 inhabitant/km^2) shows a very scattered urbanisation pattern, which originates from the medieval settlement structure. Table 1 shows the percentage of built-up land and the average distance to the nearest built-up land in Flanders, in the whole of Belgium and in five other western Euro-

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Table 1
Percentages built-up land and average distance of the open space to built-up land in the EU and the US.

	% Built-up land	Average distance to built-up land (m)
Flanders–Brussels	26	539
European union	4.8	–
Belgium	20	721
The Netherlands	11.5	1579
France	5	2385
United Kingdom	7.5	5636
Spain	1.5	6545
Germany	8	1496
United States	4.8	–

pean countries. All numbers were derived from the CORINE Land Cover map of 2000 (EEA, 2007). The built-up percentage in Flanders is 26% with an average distance to built-up area of only 539 m. Overall, it appears that the proportion of land that is built-up is significantly higher in Belgium and Flanders, than in the neighbouring countries. Moreover, in Belgium open space and urban land seem to be strongly interwoven in comparison to other western European countries (Jaeger et al., 2007). This 'rurban' landscape, characterised by a highly fragmented complex mosaic of different forms of land use, appeared since the 1960s, when the population numbers of the historical city centres decreased in favour of the population numbers in the outer urban fringe (Antrop, 2000, 2004).

The fragmented character of the Flemish landscape was enhanced by the lack of a rigid spatial planning. In contrast to for instance the Netherlands, Flanders has had a very permissive spatial policy during the 20th century. In 1995 policy makers implemented the Flemish Structure Plan (RSV), which is a conceptual plan that aims at a 'deconcentrated clustering' of dwellings and employment in the existing urban centres while preserving the remaining open space in the countryside (Albrechts, 1998, 1999; Faludi, 2005; Ministry of the Flemish Community, 2004). One of the shortcomings of the spatial planning policy in Flanders, however, is the lack of realistic scenarios of future urban development. A better understanding of the mechanisms of urban sprawl in the Flanders–Brussels region is necessary in order to develop a more realistic and feasible conceptual planning.

As government spatial planning policy is one of the main factors leading to urban sprawl (Dieleman and Wegener, 2004), the urgency for a good spatial planning policy on the regional and local level to avoid the negative consequences is obvious. Spatially explicit land use models seem to be a useful tool for urban spatial planning and for examining various policy options (White and Engelen, 2000).

Various attempts have been made to develop spatial models that simulate (sub)urbanisation processes. Most of them make use of non-urban–urban transition probabilities and planning restrictions to predict urban sprawl patterns (Verburg et al., 2004a). In many cases, logistic regression equations are used to assess the transition probabilities (Cheng and Masser, 2003; Verburg et al., 2004b). Recently, models based on cellular automata (CA), which are driven by neighbourhood relations, have become a popular modelling tool. Since the 1990s, a lot of CA-based models have been developed for different countries and regions in the world. Clarke et al. (1997) developed the SLEUTH model to predict urban growth in the San Francisco Bay area and the Washington/Baltimore corridor in the United States. Engelen et al. (2003) and White and Engelen (2000) applied a similar CA-based model in the Netherlands.

Most of these urban sprawl models were hitherto applied (i) in regions with a clear separation between urban land and the

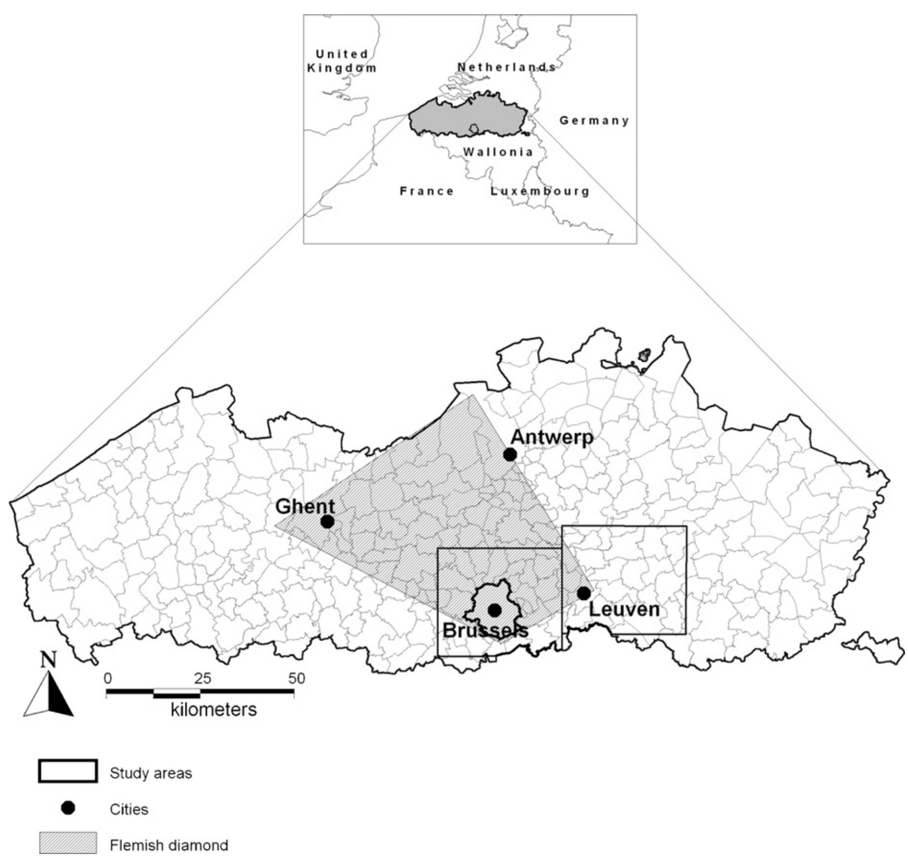

Fig. 1. Study areas in the Flanders–Brussels region.

open space around a large city or metropolitan area (Cheng and Masser, 2003; Clarke et al., 1997; Hu and Lo, 2007; Kasanko et al., 2006; Wu, 2002; Wu et al., 2006) and (ii) in more fragmented regions comprising several urban centres at coarse resolutions (>500 m) (Dendoncker et al., 2007; Verburg et al., 2004b; White and Engelen, 2000). It is, however, not known whether these modelling approaches can produce meaningful results in 'rurban' landscapes where the alternation of built-up and non-built area has resulted in a fine scaled fragmented landscape. Moreover, it is not clear at which scale models should be applied to describe such scattered urban sprawl patterns.

The objective of this paper is to examine the potential of spatial models in highly fragmented urban areas. Two study areas in the Flanders–Brussels region, which is one of the most fragmented and urbanised areas in the world, are taken as example applications: (i) the city of Brussels and its suburbs and (ii) the Hageland region which is a semi-urban area east of Brussels in which a lot of new built-up area has appeared during the last decades. Firstly, urban sprawl in the two study areas is mapped by means of the interpretation of remote sensing imagery for three different years: 1976, 1988 and 2000. Next, the observed expansion of the built-up land in the period 1976–1988 is used to calibrate the model parameters of a widely used empirical land use/land cover model. Finally, the land cover map of the year 2000 is used to validate the model predictions in both study areas at various spatial resolutions.

2. Material and methods

2.1. Study area

The Flanders–Brussels region is situated the heart of Europe and is one of the most densely populated areas in the world (Fig. 1). The region has a population of approximately 7.1 million people. The scattered appearance of the urban area in the region was already an important feature in the middle ages. The high road density of the area triggered the diffusion process of the urban areas after WWII. The availability of accessible, cheap open space attracted large-scale retail activities, which in their turn attracted residential areas (Antrop, 2000, 2004; Ministry of the Flemish Community, 2004). The suburbanisation process resulted in ribbon development that made Flanders a highly fragmented area with the most 'American-like' spatial pattern of urbanisation in Europe (Holden and Turner, 1997) and with a built-up area occupying more than 25% of the territory.

The highest population density is found in the area circumscribed by the Brussels–Antwerp–Gent–Leuven agglomerations that is known as the 'Flemish Diamond' (Fig. 1). The 'Flemish diamond' is a polynucleated urban system which concentrates high-quality industrial, commercial, service, logistic and research activities and is the main centre of economic development in the Flanders–Brussels region.

In order to study the urban sprawl patterns, two adjacent but contrasting study areas of $\pm 1000\,\mathrm{km}^2$ were selected: the Hageland region east of Brussels and the Brussels-Capital region (Fig. 1).

The Hageland region is a semi-urbanised area that includes the regional city of Leuven and three smaller cities and is situated at the border of the Flemish diamond. The area includes parts of 34 municipalities, housing almost 400,000 inhabitants. The regional city of Leuven is situated in the west of the study area and is surrounded by seven towns of the inner and outer urban fringe of Leuven. The other towns are situated in the rural commuting zones of Leuven and Brussels or can be seen as rural towns or small rural cities. The second study area is situated in the interior of the 'Flemish diamond', around Brussels. The Brussels-Capital study area has more than 1.5 million residents and is comprised of the 19 municipalities of the Brussels-Capital region, 14 Flemish towns situated in the inner urban fringe of Brussels and parts of 17 towns from the Brussels outer urban fringe and rural commuting zone.

During the last two decades, the predominant form of land cover change in both study areas has been the transformation of arable land and grassland to built-up area and more specifically to new residential area (FPS Economy, SMEs, independent Professions & Energy, 2006). Since the 1990s, especially the rural commuting zone has become increasingly popular for new residents (Vanneste et al., 2007). The city centre of Brussels, on the other hand, knew its most rapid growth in the 1950s and 1960s, similar to other Belgian and European urban cores (Kasanko et al., 2006). Urbanisation thus acted as a diffusion wave that first affected the largest cities. Starting from the 1960s, it gradually spread towards smaller towns and settlements and now it is practically affecting the whole countryside (Antrop, 2004).

This evolution of the built-up area has caused severe fragmentation in the landscapes of the two study areas. In the Hageland region, historically, ribbon development had already occurred. This phenomenon, however, was aggravated due to the urban expansion. In the Brussels area the very few open spaces that still exist are highly fragmented by residential areas, infrastructure and commercial and industrial zones (Ministry of the Flemish Community, 2004).

2.2. Detecting urban sprawl

Land cover maps for the whole of Flanders and Brussels for 1976, 1988 and 2000 were created by using Landsat-MSS (1976), Landsat-TM (1988) and Landsat-ETM+ (2000) images. To accommodate image shortages, e.g. due to cloud cover, a deviation of 2 years from the baseline data was allowed for the acquisition of the satellite images. Each Landsat image was geometrically registered to the Belgian Lambert-1972 projection using control points on 1:10,000-scale topographical maps. The data were resampled to a common spatial resolution of 30 m using the nearest neighbourhood algorithm in order to keep the original brightness values of the pixels unchanged. The resulting root mean square planimetric error of each registered image was less than 0.57 pixels (i.e. 17.1 m).

Land cover maps of 1976, 1988 and 2000 were derived from these registered Landsat images through a supervised maximum likelihood classification using all seven bands of the Landsat-TM and Landsat-ETM+ and all four bands of the Landsat-MSS. Delineation of the training areas was based on (i) visual interpretation of the satellite images, (ii) 1:10,000-scale topographical maps of Flanders and Brussels and (iii) agricultural parcel maps of Flanders. The classified land cover classes are built-up land, arable land, grassland and forest. To simplify the data and to eliminate noise, isolated pixels were removed from the map by using a 3-by-3-majority filter. The accuracy of the three classified land cover maps was checked with a random sample of 250 control points. The reference data were obtained from aerial photographs at a scale of 1:20,000. Overall accuracy of the final land cover map of Flanders and Brussels was 77.6% for 1976, 82.8% for 1988 and 82.3% for 2000. Fig. 2 shows the land cover maps at the extent of the study areas.

Finally, for each study area, the land cover classes were reclassified into two categories, built-up and non-built. The built-up category contains all paved areas including residential and commercial zones, industry, roads and parking spaces. The accuracy of the six maps showing the built-up area for each study area for 1976, 1988 and 2000 was checked with a random sample of 150 control points. The user's (P_U) and producer's (P_P) accuracies for built-up land are shown in Table 2.

Landscape fragmentation by built-up land was assessed in both study areas using the following fragmentation indices: a dimensionless density index (D) and a shape index (P/A, in km/km^2). The density index (D) is the ratio between the 'gross' built-up area and

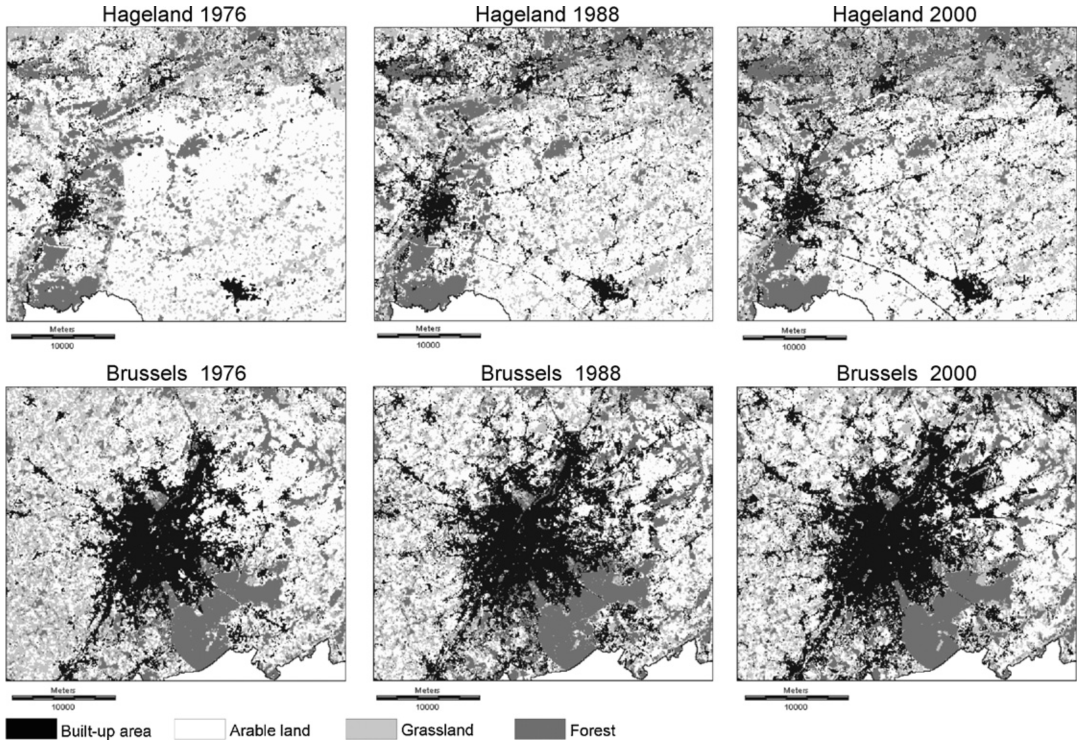

Fig. 2. Land cover in the Hageland study area and the Brussels study area in 1976, 1988 and 2000.

the 'net' built-up area. The 'net' built-up area is the total area of built-up land in a study area based on the original 30 m resolution land cover maps. The 'gross' built-up area, on the other hand, was calculated by counting the total area of 1 km^2 blocks that contained at least 1 built-up pixel. Large values of the density index point to a scattered urban landscape, while small values correspond with more compact urban landscapes.

Shape indices are widely used in landscape ecology applications (Gustafson, 1998). In this study, the perimeter–area ratio (P/A) was calculated for each patch of built-up land after which an area-weighted average was calculated for the entire study area. This shape index measures the complexity or irregularity of the built-up patches. Landscapes that are made up of many compact shapes show low values of P/A, while high P/A values are associated with more elongated and irregular patches.

2.3. Modelling urban sprawl

In this study, the Geomod model (Pontius et al., 2001) was used as a representative example application because (1) the model makes use of transition probabilities, which is the key concept in the majority of existing urban sprawl models, (2) it allows building in spatial constraints and (3) it has relatively low data demands.

The model predicts the pattern of the one-way transition from one land cover state to another. It was originally designed to simulate the loss of tropical forest, but has been successfully applied for simulating the transformation from non-built to built-up land (Pontius and Malanson, 2005).

Table 2
User's (P_U) and producer's (P_P) accuracy for built-up land in the Hageland and Brussels study area.

	Hageland			Brussels		
	1976	1988	2000	1976	1988	2000
P_U	81%	89%	86%	89%	96%	79%
P_P	81%	89%	93%	70%	87%	92%

Geomod was used to predict the expansion pattern of the built-up land in the period 1988–2000. The model was run at a 30 m × 30 m resolution, which is the original resolution of the land cover maps. Land cover maps of 1976 and 1988 were used for model calibration. The model output was validated by comparing the predicted patterns with the land cover map of 2000.

The model procedure consists of (i) the assessment of the number of new built-up pixels and (ii) allocation of the new built-up pixels taking into account the suitability of the non-built-up land.

The total number of new built-up pixels in 2000 was assessed external to the model by means of a linear extrapolation of the 1976–1988 trend. Fig. 3 shows that this extrapolation resulted in an underestimation of the built-up area in both study areas.

The suitability of a pixel for built-up land was derived from the properties of the existing built-up pixels using the following categorised variables: (i) distance to various types of roads, (ii) distance to the nearest motorway entrance, (iii) the employment potential and (iv) the flood risk. The distance to the different road types and to the motorway entrance points was derived from a vector dataset made available by the Flemish Land Agency. The vector dataset identifies the following categories of roads: motorways, national roads, secondary roads and local roads (Fig. 4). For each pixel, the distance to the different road categories and to the motorway entrance points was calculated with the DISTANCE-calculator of IDRISI®.

The employment potential is a relative measure of accessibility to jobs and was calculated by using the gravity-based mathematical formula proposed by Hansen (1959):

$$E_i = \sum_{j=1}^{n} \frac{J_j}{D_{ij}^2}$$

where E_i = the employment potential of pixel i, J_j = the total number of jobs in town j in the year 2000, D_{ij} = the distance between pixel i and town j, n = the number of towns used in the calculation.

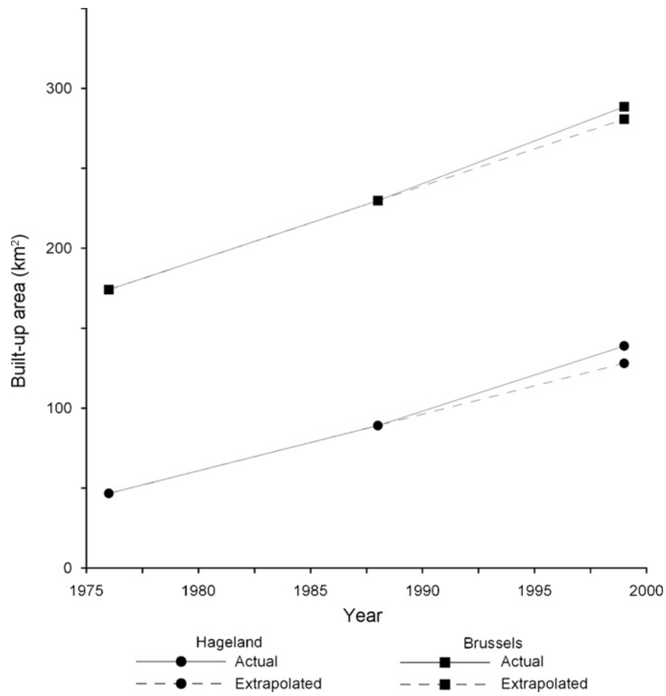

Fig. 3. Linear extrapolation of the built-up area in the Hageland study area and the Brussels study area.

All administrative municipalities in Belgium were taken into account to calculate the employment potential map (Fig. 4). Employment data for the year 2000 were obtained from the study service of the Flemish government.

The flood risk data used in this study consists of a binary map compiled by the Flemish Environment Agency. The map is based on observed floods and on model simulations and makes a distinction between pixels with a high flood risk (recurrence interval of a flood <25 years) and pixels with a low flood risk (recurrence interval of a flood >25 years). The predicting variable 'flood risk' could not be taken into account inside the Brussels-Capital region since the flood risk map was not available for this area (Fig. 4).

For all categories (k) of the predicting variables (a), the relative frequency of existing built-up pixels (P_a) was calculated. Suitability maps were created by computing a weighted sum of these relative frequencies, using the following equation:

$$S_{i(t1)} = \sum_{a=1}^{n} W_a . P_{a(t0)}$$

where $S_{i(t1)}$ = the suitability of pixel i for built-up land at time step $t1$, a = a particular (categorical) predicting variable, n = the number of predicting variables that were used in the analysis, W_a = the weight of predicting variable a, $P_{a(t0)}$ = the relative frequency of existing built-up pixels (at time step $t0$) in category k of predicting variable a, where pixel i is a member of category a_k.

The weighting coefficients W_a of the predicting variables were calibrated in two calibration phases using the land cover maps of 1976 ($t0$) and 1988 ($t1$). First, Geomod derived the P_a values for

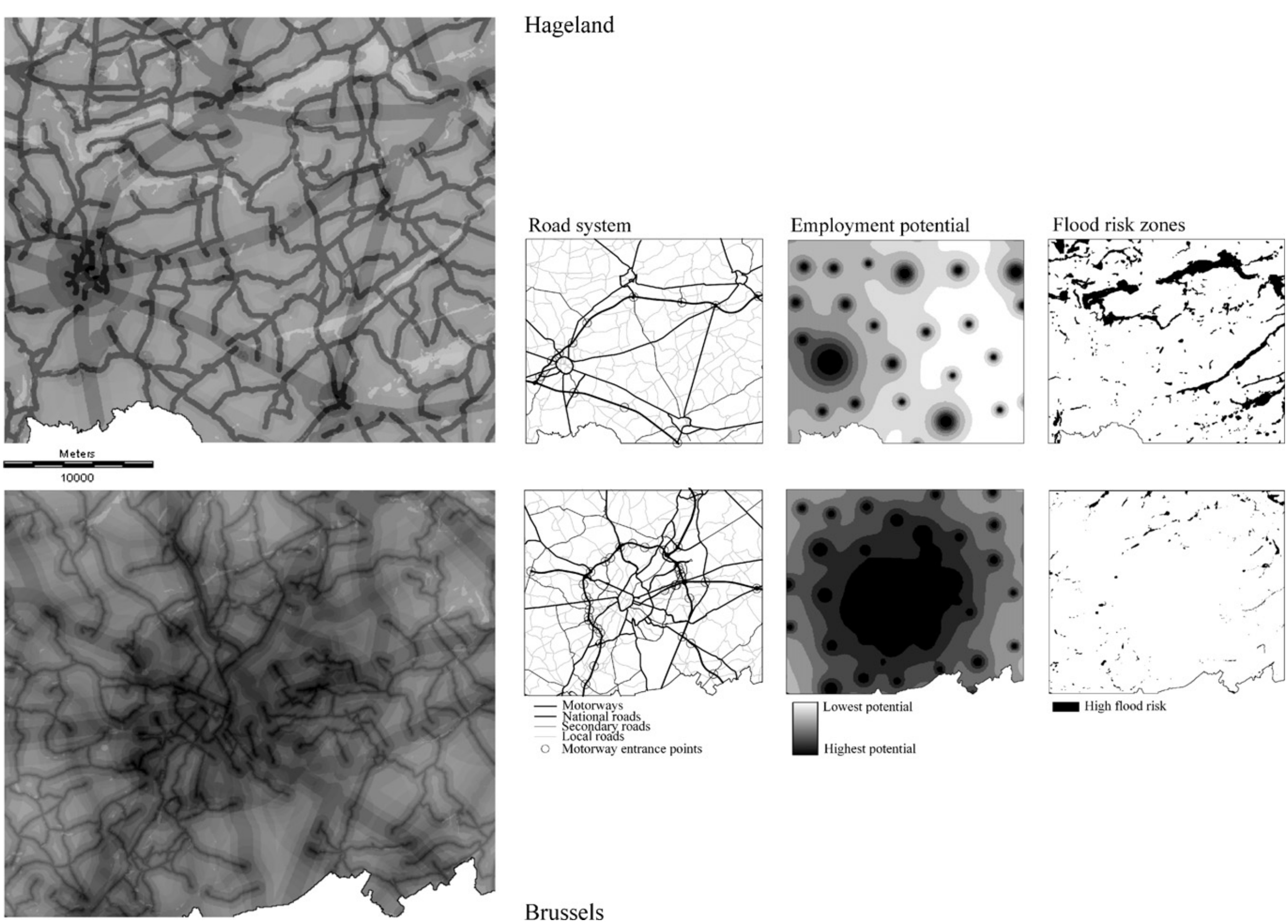

Fig. 4. Suitability maps created by Geomod (left) and variables used in the study (right).

period $t0$ by calculating the ratio of the number of pixels in category a_k that were built-up in 1976 to the total number of pixels in that category. Next, the model was run for a range of W_a values to reconstruct the 1988 land cover. In the first calibration phase the weighting coefficient W_a for each predicting variable a was varied from 0 to 1 in increments of 0.25, while the weighting coefficients of all other predicting variables were held constant at intermediate levels. For each set of weighting coefficients, the simulated suitability map S_i was compared with the actual 1988 land cover map using the ROC-procedure (Pontius and Schneider, 2001). The ROC-procedure evaluates the model's ability to specify the location of change, independently from the quantity of change and varies between 0 and 1. During the second calibration phase the set of weighting coefficients was refined by varying W_a in smaller increments (0.01–0.05) within a narrowed range around the parameter value that produced the highest ROC. Fig. 5 illustrates this procedure by showing the calibration plots of two of the predicting variables. The set of W_a coefficients that produced the suitability map with the highest ROC was subsequently used to simulate the built-up land in 2000. Suitability maps for both study areas are shown in Fig. 4.

Allocation of the new built-up land in 2000 was based on three decision rules. The first rule dealt with the suitability map for 2000, which was based on the 1988 ($t0$) land cover map and the weighting coefficients W_a calibrated for the period 1976–1988. New built-up pixels were allocated by selecting non-built pixels with the highest suitability until the required quantity of built-up pixels was reached. The second rule concerned persistence of the expanding land cover category, in this case built-up land. This means that pixels that were built-up in 1988 could not be converted into non-built pixels in the 2000 simulation. The third decision rule concerned the neighbourhood constraint. With this model option turned on, Geomod restricts new built-up land to locations within a small square window around an existing built-up pixel. This rule is useful when simulating urban sprawl phenomena, as the new urban land is spreading from existing urban areas. The neighbourhood option was calibrated for the period 1976–1988 by running the model with and without (unconstrained) the neighbourhood constraint and using several widths of the search window (3×3, 5×5, 7×7, 9×9 and 11×11). The alternative that resulted in the highest agreement between the simulated land cover map of 1988 and the actual land cover in 1988 was used to simulate the built-up land in 2000.

2.4. Validation

The performance of the different model runs was assessed by comparing the predicted land cover maps of 2000 with the observed land cover map of 2000. Pontius et al. (2004) proposed four characteristics that should be taken into account when validating spatial land use or urban sprawl models: (a) an estimation of the error sources, (b) comparison of the model result with the results of a null model, (c) comparison of the model results with a random model and (d) analysis at multiple scales.

Firstly, the error budget decomposed the total model error into disagreement due to quantity and disagreement due to location. In this study, errors due to quantity were caused by the extrapolation of the 1976–1988 trend, while errors due to location were caused by the allocation procedure used by Geomod. Secondly, the performance of the different model runs was compared to the performance of a null model, which is a model that predicts pure persistence of the land cover, and to the performance of a random model. The random model simulated a land cover map of 2000 based on the same quantity of new built-up pixels that was predicted for the Geomod model (Fig. 3). For both study areas the predicted number of new built-up pixels was allocated by randomly selecting non-built pixels and converting them to built-up land until the required number of built-up pixels was reached. The comparison with both the null model and the random model was made in order to evaluate Geomod's ability to locate new built-

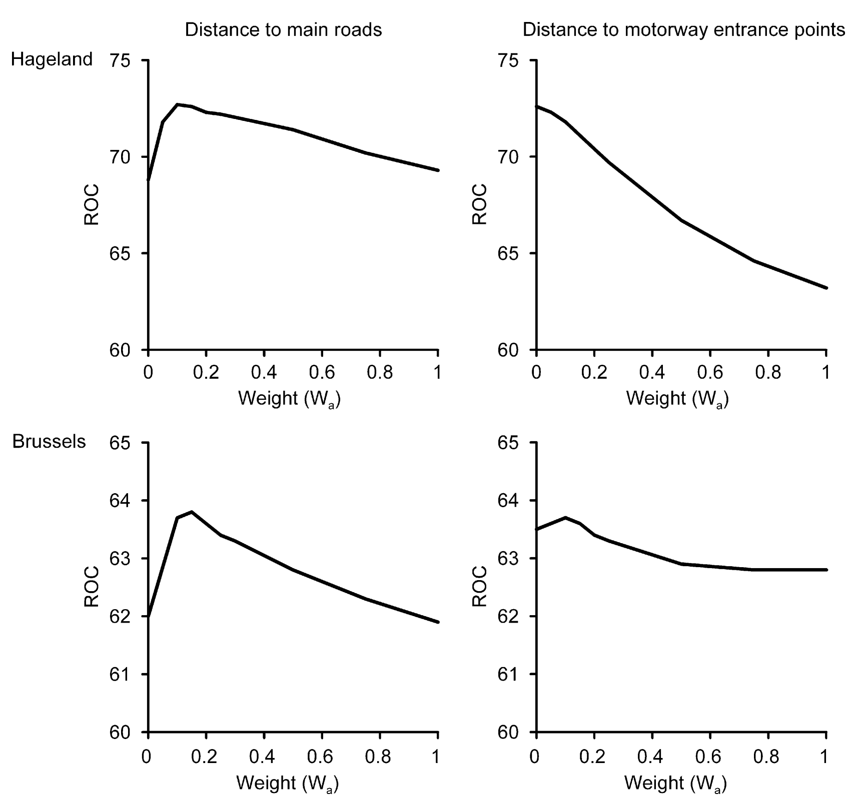

Fig. 5. Calibration plots for two of the predicting variables.

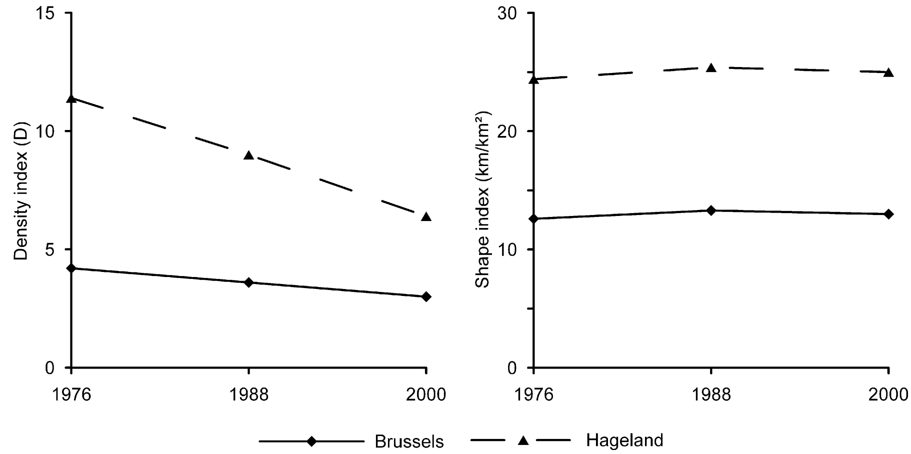

Fig. 6. Comparison of the fragmentation indices for both study areas.

up pixels. Finally, the performance of the different model runs was evaluated at multiple resolutions in order to see how scale influenced the assessment. This analysis was carried out by aggregating neighbouring pixels at the fine (30 m) resolution into coarser pixels both on the predicted and on the observed land cover map.

The null resolution was the spatial resolution at which the Geomod runs performed equally well as the corresponding null model.

3. Results

Fig. 2 shows the compiled land cover maps from 1976, 1988 and 2000 for both study areas. The predominant land cover change during the period under study was the conversion of open land (arable land and grassland) to built-up land. In the Hageland study area, 5.1% of the total area was built-up in 1976, while more than 15% became built-up after 2000. Of this increase in urban land, 86% resulted from arable land and 9% from grassland. The size of the forested area in the Hageland study area has not changed much since 1976 given that almost 60% of the total forest cover is situated in zones designated to forest and natural areas by the Flemish zoning plan. According to this zoning plan, which was developed in the 1960s and 1970s, urban development in forested and natural zones is strictly prohibited. In the more urbanised Brussels study area, built-up area grew from 19.1% in 1976 to 31.7% of the total study area in 2000. Here, the main contribution again came from arable land (71%) and grassland (20%). Although the Hageland study area is less urbanised than the Brussels region, the built-up land in the Hageland region is much more fragmented than the built-up land in the Brussels region: both the values of the density index (*D*) and the shape index (*P*/*A*) are much higher for the Hageland study area than for Brussels (Fig. 6). The Hageland area shows a rather complicated and scattered landscape, that consists of a number of urban centres, connected by elongated 'urban corridors', in contrast to the relatively compact city centre of Brussels. In both study areas, however, the decreasing *D* values indicate that the built-up area is growing more compact in time. This means that new urban land is mainly developing around the existing urban cores ('sprawl') and in the remaining open spaces within urban centres ('densification'). The complexity of the built-up patches (*P*/*A*), on the other hand, is relatively constant in time (Fig. 6).

Spatial patterns of the growth of built-up land between 1976 and 2000 are shown in Fig. 7. A visual analysis of the spatial pattern of the new built-up area in the 1976–2000 period shows that:

(i) New built-up land tends to cluster around the existing cores, while new developments in the open area are rather scarce, as was already demonstrated by the decreasing D values. In the Hageland study area, especially the area in the vicinity of the main city of Leuven appears to be attractive for new built-up land.
(ii) Accessibility seems to control the spatial pattern of built-up area to a large extent. Most of the new built-up area is situated

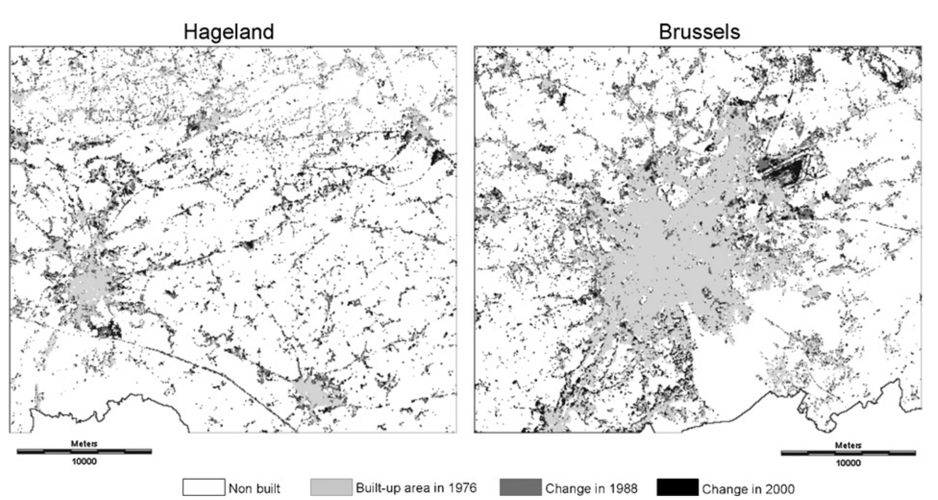

Fig. 7. Expansion of the built-up area between 1976 and 2000.

Table 3
Calibrated weights (W_a) of the controlling variables.

	Weights (W_a)	
	Hageland	Brussels
Distance to main roads	0.10	0.15
Distance to secondary roads	0.03	0.17
Distance to local roads	0.25	0.33
Distance to motorway entrances	0.00	0.10
Employment potential	0.05	0.00
Flood risk areas	0.15	0.15

adjacent to or near local and national roads. Accessibility to the motorways seems to be of minor importance in both study areas.

(iii) New developments seem to avoid flood prone areas.

The findings drawn from this visual analysis of the urban sprawl patterns are confirmed by the suitability maps, computed by Geomod (Fig. 4). The weights of the different factors were calibrated using the 1976–1988 observations and are shown in Table 3. The results show that in both study areas the most important factor is the distance to local roads: new built-up land is mainly developing in the immediate surroundings of the local roads. National roads and secondary roads are attracting built-up land to a lesser extent. Distance to the motorway entrance points is a non-significant variable in the Hageland region, while its role in attracting new urban development in the Brussels study area is moderate. The flood risk is a significant contributing factor in both study areas and is repelling the development of built-up land. The accessibility to the employment market is a minor but significant controlling factor in the Hageland area: new built-up land is mainly developing in the zones with a higher employment potential in the vicinity of the city of Leuven and in the west of the study area near to the centres of employment around Brussels.

The suitability maps based on the calibrated weights were used to run the model with and without a neighbourhood constraint in order to obtain an optimal allocation of the newly built-up area in the period 1976–1988.

Table 4
Pixel-to-pixel agreement (observed vs. predicted) of the tested models for the land cover in 1988.

	Brussels	Hageland
Unconstrained	90.61	92.68
3×3 window	92.42	93.99
5×5 window	91.78	93.79
7×7 window	91.35	93.43
9×9 window	91.15	93.25
11×11 window	91.03	93.12

Table 4 shows the pixel-to-pixel agreement between the observed built-up patterns in 1988 and the patterns predicted by the different Geomod runs. The model run with the finest (3×3) search window for the neighbourhood constraint produces the land cover map with the highest agreement in both study areas. Larger search windows result in larger errors and the unconstrained model run shows the lowest agreement with the observed built-up patterns. Consequently, a 3×3 constrained neighbourhood was used to simulate built-up land in 2000.

Fig. 8 shows the results of a comparison between the simulated and observed land cover patterns in 2000. In both study areas the observed error is relatively small: pixel-to-pixel agreement is over 93% in the Hageland region and over 92% in Brussels. This observed total error is mainly made up of disagreement due to the location of the new built-up land. The disagreement due to quantity is only 0.78% in the Hageland region and 0.35% in Brussels. This finding is in agreement with Fig. 3 showing that a linear extrapolation of built-up area leads to a smaller underestimation in Brussels than in the Hageland study area.

This relative high agreement, however, does not indicate that the model provides additional information beyond what would have been predicted without using any model: most pixels on the predicted image have a persistent land cover, implying that if a pixel was built-up in 1988, it automatically remains built in 2000. Fig. 8 shows that for both study areas, the results of the Geomod runs are significantly less accurate than the results of the corresponding null model, while they are more accurate than the random model when the results are interpreted at the resolution of the original data (i.e.

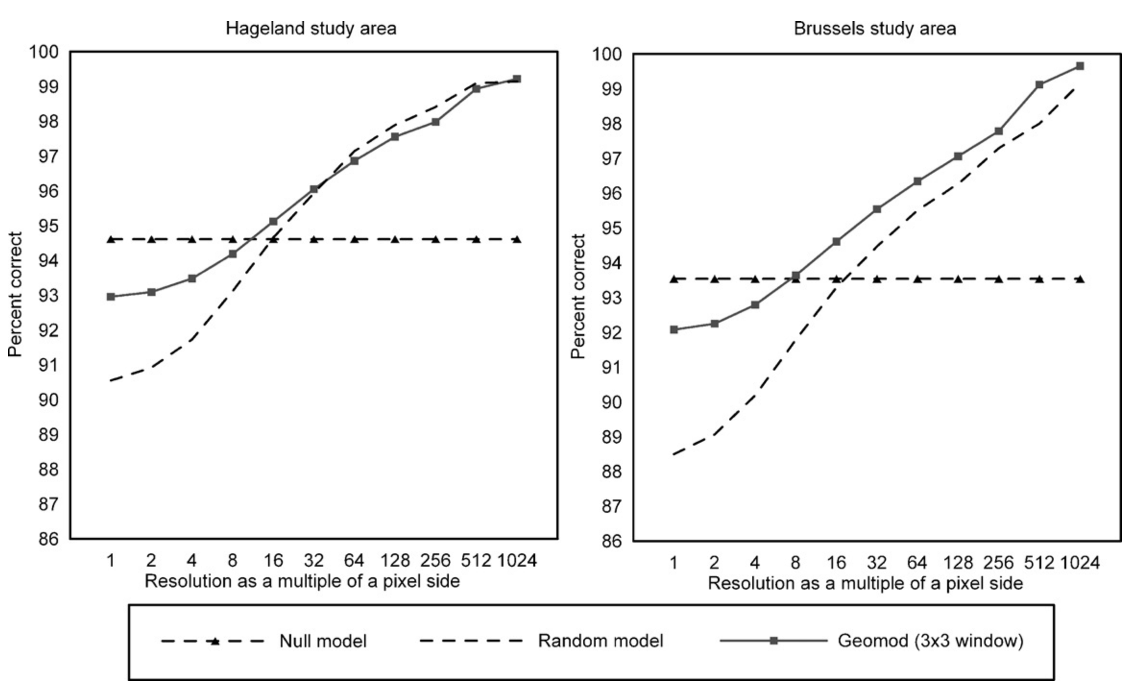

Fig. 8. Percent correct at multiple resolutions for the Geomod run, the null model and the random model.

30 m). This implies that one has to be very careful when interpreting the model results at this high resolution: although Geomod performs better than a model that randomly allocates new built-up pixels, the model is not able to make significant better predictions than a model that predicts pure persistence of the land cover. Fig. 8 shows the results of the different model runs at multiple resolutions. In order to evaluate the performance of the models at coarser resolutions, the pixels of both the observed and the predicted land cover maps were aggregated and the pixel-to-pixel agreement of the new coarser pixels was determined. At a coarser resolution the error due to location decreases since the errors due to small displacements of the built-up pixels are eliminated. The error due to quantity, on the other hand, is independent of resolution. Consequently, the total agreement of the Geomod runs and of the random model is increasing at coarser resolutions, while the agreement of the null model remains constant.

Fig. 8 shows that in the Hageland study area at a resolution of approximately 330 m (11 times the resolution of the raw data) the Geomod run with a 3×3 neighbourhood constraint performs as well as the null model. The null resolution of this model run in the Brussels study area is 240 m (8 times the resolution of the raw data). In the Brussels region, the random model is outperformed by Geomod at all analysed resolutions, while in the Hageland study area, the random model becomes the most accurate model starting from a resolution of approximately 1.2 km (40 times the resolution of the raw data). This implies that although all model runs show a somewhat lower pixel-to-pixel agreement at the resolution of the original data, Geomod is more accurate in the compact Brussels study area than in the more fragmented Hageland region.

4. Discussion and conclusions

Since the 1970s, the most important land cover change that took place in the Flanders–Brussels region has been the conversion of arable land and grassland to built-up area. This study indicates that there are some significant factors that control the urban sprawl pattern in the Flanders–Brussels region. Accessibility and neighbourhood interactions are important determinants of the urban sprawl pattern in Brussels. This corresponds with findings from other cities in the world (e.g. Aguayo et al., 2007; Cheng and Masser, 2003; Clarke et al., 1997; Hu and Lo, 2007). Moreover, this study showed that the same factors are controlling the urbanisation pattern in highly fragmented semi-urban areas such as the Hageland region. Although the controlling factors are similar, the urban growth patterns in the selected study sites show some important differences. The Brussels study area shows a rather concentric urban growth around the city of Brussels, while the urban expansion pattern in the Hageland region is much more complicated due to the existence of several smaller urban cores that are connected to each other by the road network. Due to its status as a regional employment centre, the city of Leuven is attracting urban development just like the city of Brussels, but another significant part of the urban expansion is controlled by the road network. Both the national roads and the relatively small local roads are important attractors for new urban development. This has led to the formation of the typical Flemish 'urban corridors' mainly consisting of commerce and small industry when two urban centres get connected (Antrop, 2000). Distance to motorway entrance points, on the other hand, does not contribute much to the explanation of the spatial pattern of urban expansion in either of the study areas. This contrasts with the situation in the United States where motorways and their entrance points are of major importance for the localisation of newly urbanised areas (e.g. Clarke et al., 1997). The main reason for this discrepancy is the scale of the study areas, which is too small to capture the influence of the motorways on urban development. On a regional scale, motorways can be a pull-factor for built-up land, but on local scales (<10 km) this effect is not present because people prefer to avoid the direct neighbourhood of motorways because of noise and air pollution. Therefore the distance to a local or national road that is connected with a motorway plays a much more important role.

An important finding of this study is the fact that both the development of urban corridors as concentric growth, two very distinct forms of urban growth, can be modelled with a relatively simple spatial model: in both study areas the Geomod simulation shows better agreement with the reference land cover map of 2000 than a random simulation that predicts the same amount of change. It is important, however, to state carefully the degree to which the model is valid. Our study pointed out that at the level of the individual grid cells the Geomod application did not have any additional predictive power over the null model. Geomod only produces significant urban sprawl patterns at spatially aggregated resolutions above $240\,\text{m} \times 240\,\text{m}$ in the Brussels region and at resolutions above $330\,\text{m} \times 330\,\text{m}$ in the Hageland region, which is quite acceptable given that the land cover maps used as input have omission and commission errors around 10–20%. Moreover, in the Hageland region Geomod seems to be valid only for a limited range of resolutions. At the resolution of the original data ($30\,\text{m} \times 30\,\text{m}$) up to a resolution of $330\,\text{m} \times 330\,\text{m}$, the null model shows a better agreement with the observed urbanisation patterns than the Geomod predictions, while a random model performs better than Geomod at resolutions coarser than $1.2\,\text{km} \times 1.2\,\text{km}$. Geomod thus seems to perform better for rather compact urban areas than for highly fragmented areas that consist of several urban cores and ribbon development.

As most of the model error can be attributed to disagreement due to location, possible improvements of the model for the Hageland region are (i) the use of a more accurate suitability map and (ii) the incorporation of more complex cellular automata allocation rules.

A more accurate suitability map should, in principle, allow increasing the pixel-to-pixel agreement and decreasing the null resolution of the model. Because of the lack of a rigid spatial planning in the studied time span (1976–2000), which resulted in a small-scale fragmentation of the built-up area, the location of new built-up land is highly susceptible to local and random factors such as local policy decisions at the level of municipalities, landscape attractivity and landownership. Since it is impossible to take such local conditions into account in a computational model a further decrease of the null resolution is very unlikely. The implementation of the Flemish Structure Plan (RSV) in 1995 should lead to a less chaotic urbanisation pattern in the future, which might be easier to model. Due to its recent implementation, however, the impact of the RSV is not yet fully visible in the urban development patterns.

Secondly, this study pointed out that neighbourhood effects control to a large extent the spatial pattern of urbanisation: constrained model applications perform significantly better than the unconstrained model run and the smaller the search window, the better the performance of the model. This means that new built-up land is preferably developing in the neighbourhood of an existing built-up pixel, while spontaneous new development in the open space is rather scarce. This finding can be related to the trend of the fragmentation indices that was observed to be decreasing in time. This decreasing trend indicates that the built-up environment is growing more compact. This is in accordance with the guidelines of the RSV (Ministry of the Flemish Community, 2004), but does not result from the implementation of the RSV as the densification process has already been initiated in the period 1976–1988. The finding, however, suggests that cellular automata might be used to ameliorate the spatial representation of small-scale fragmentation patterns. In this study, new urban land was allocated to the grid cells with

the highest suitability around existing built-up pixels without taking into account the characteristics of the neighbouring land. This allocation procedure could be improved by incorporating push and pull-factors between various land cover types. A grid cell may for example be more attractive for residential land in the neighbourhood of a forest than in the neighbourhood of an industrial zone. The major drawback of such an approach, which limits it applicability, is the complexity of the model since many more model parameters need to be calibrated (Barredo et al., 2003; de Nijs et al., 2004; White, 1998).

Besides these remarks, the results from this study point out that a low data-demanding model based on land use suitability mapping, performs relatively well if the results are interpreted at the appropriate scale. This should encourage land managers and policy makers to use such models as tools for explorative planning, scenario development and environmental impact assessment.

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